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An interferometric-based optical read-out for the LISA Proof-Mass

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Presentation Overview

- **Motivation**

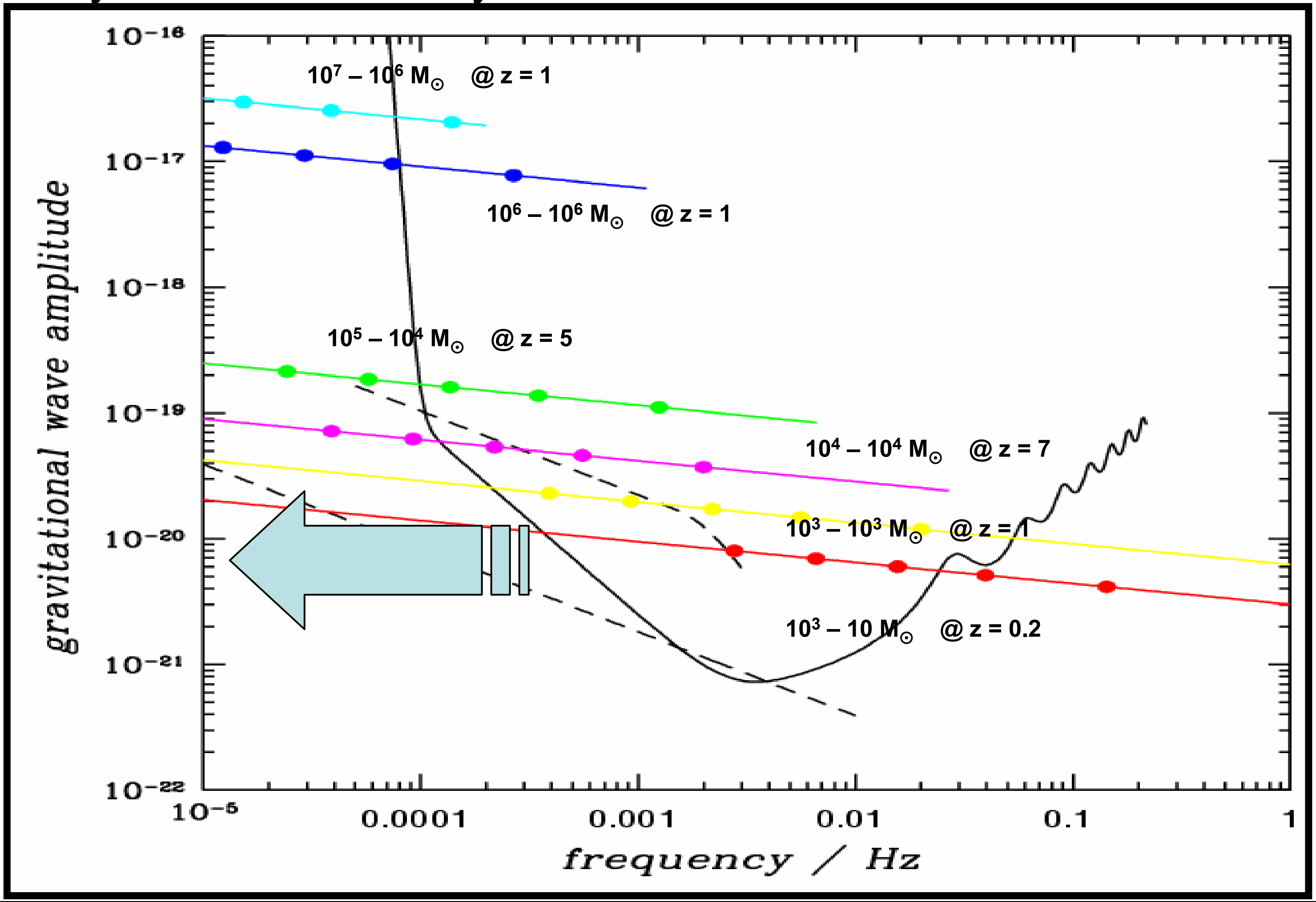
- **A new homodyne Interferometer**
  - Design concept
  - Homodyne fringe interpolation
  - VCSEL laser diode characteristics
  - Current experimental set-up

- **Sensitivity results**

- **Summary and future work**

Motivation

Our *goal* is to improve LISA's low frequency sensitivity to enable the study of massive binary black hole coalescences.

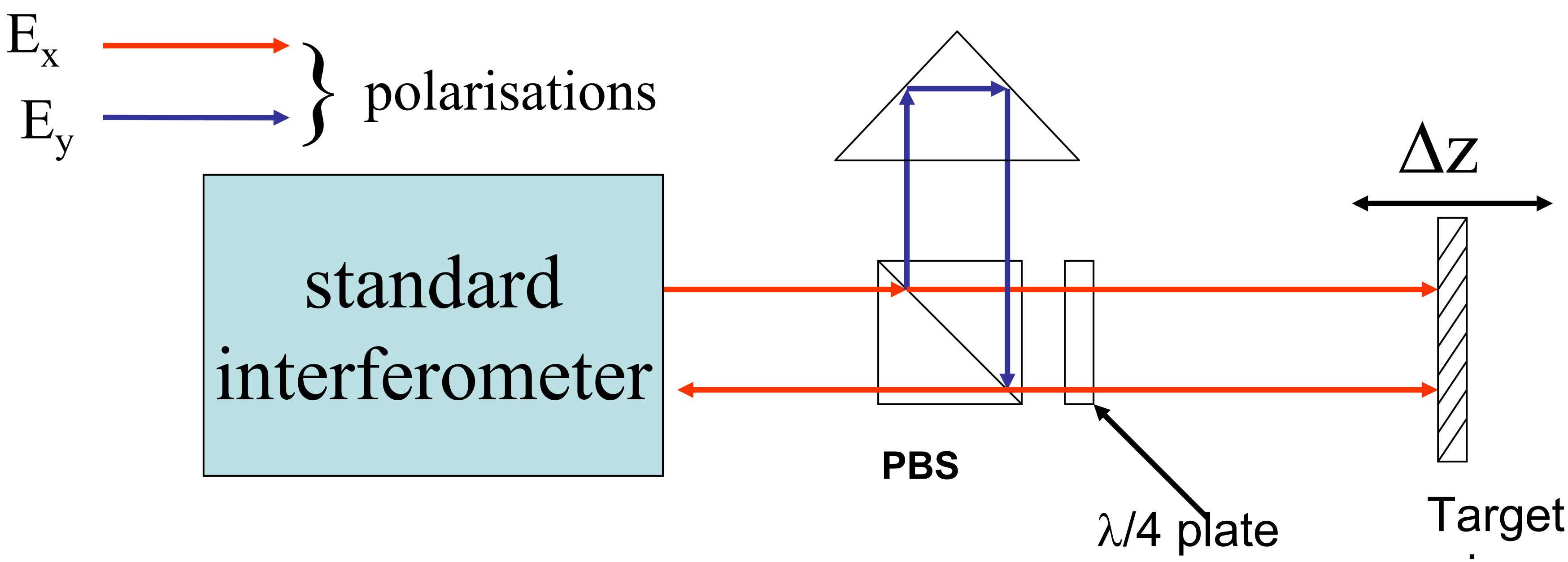


Design principles

- To ensure good low frequency stability we avoid active parts that generate heat, that can age, thermally expand, have hysteresis…
- We aimed for a compact design with as few components as possible
- Interferometer should be as insensitive to tilt as possible to ensure that the sensor is robust against proof mass rotation
- Final design is a development of work done at NPL(UK) (Downs et al. 1984) and also Greco et al 1995

A new homodyne Interferometer

Starting concept: Hybrid retroreflector.

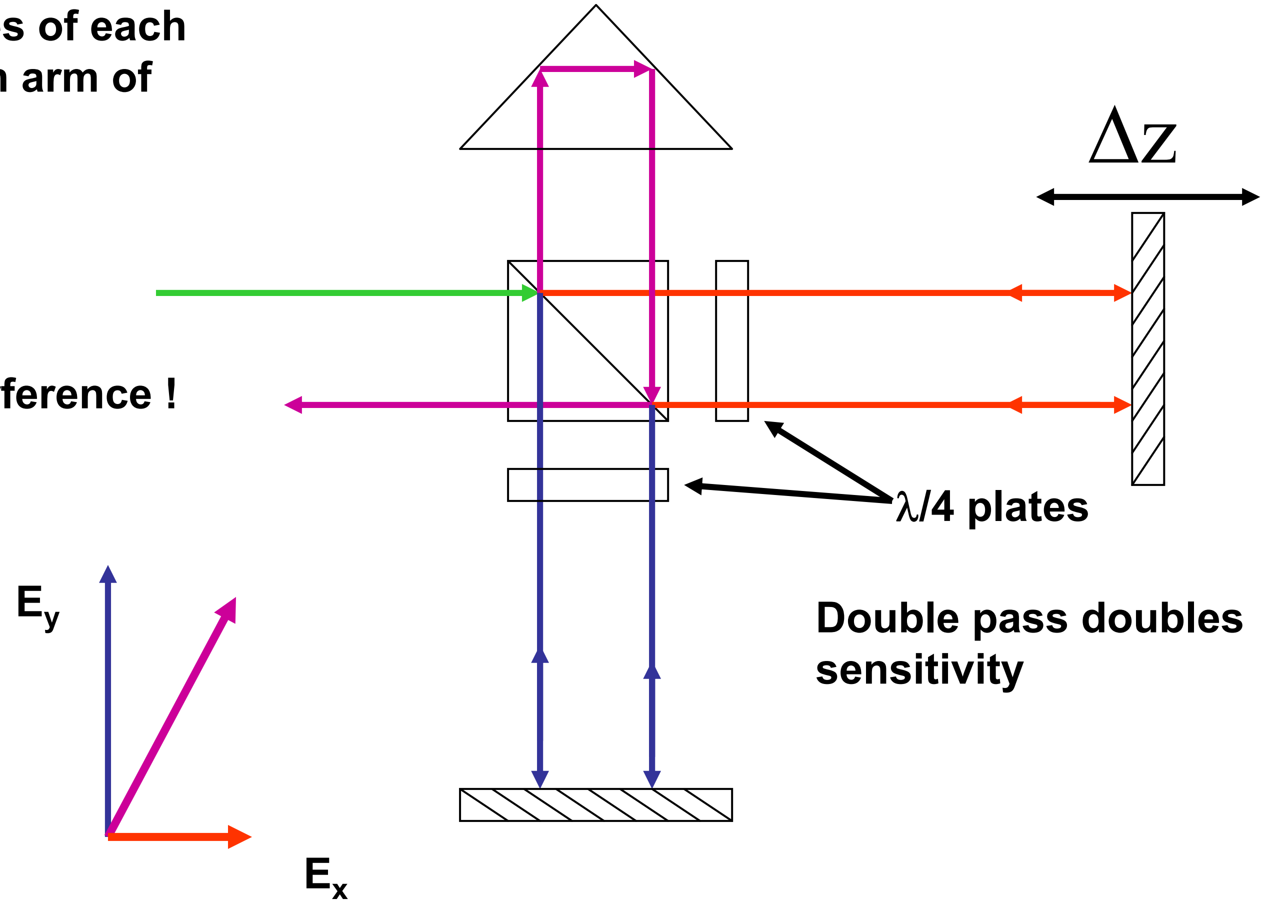


Standard use of cube-corner retroreflector for measurement arm of interferometer to avoid sensitivity to angular motion of target mirror.

A new homodyne interferometer

Hybrid retroreflector is incorporated symmetrically into both arms of Michelson interferometer.

Inject equal intensities of each polarisation into each arm of interferometer.

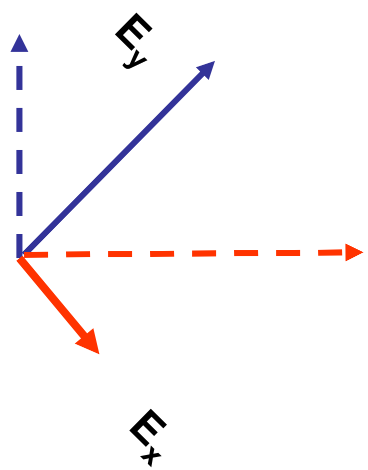


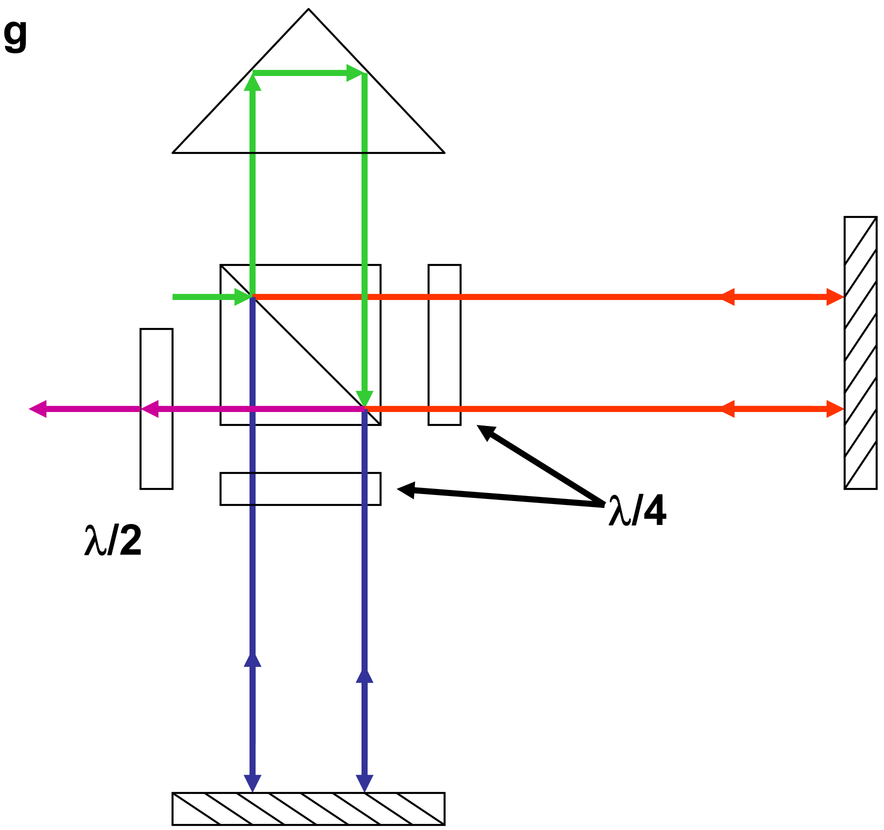
$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} \propto \begin{pmatrix} e^{i\phi} \\ 1 \end{pmatrix}$$

$$\phi = \frac{2\pi}{\lambda} \cdot 4\Delta z$$

A new homodyne Interferometer

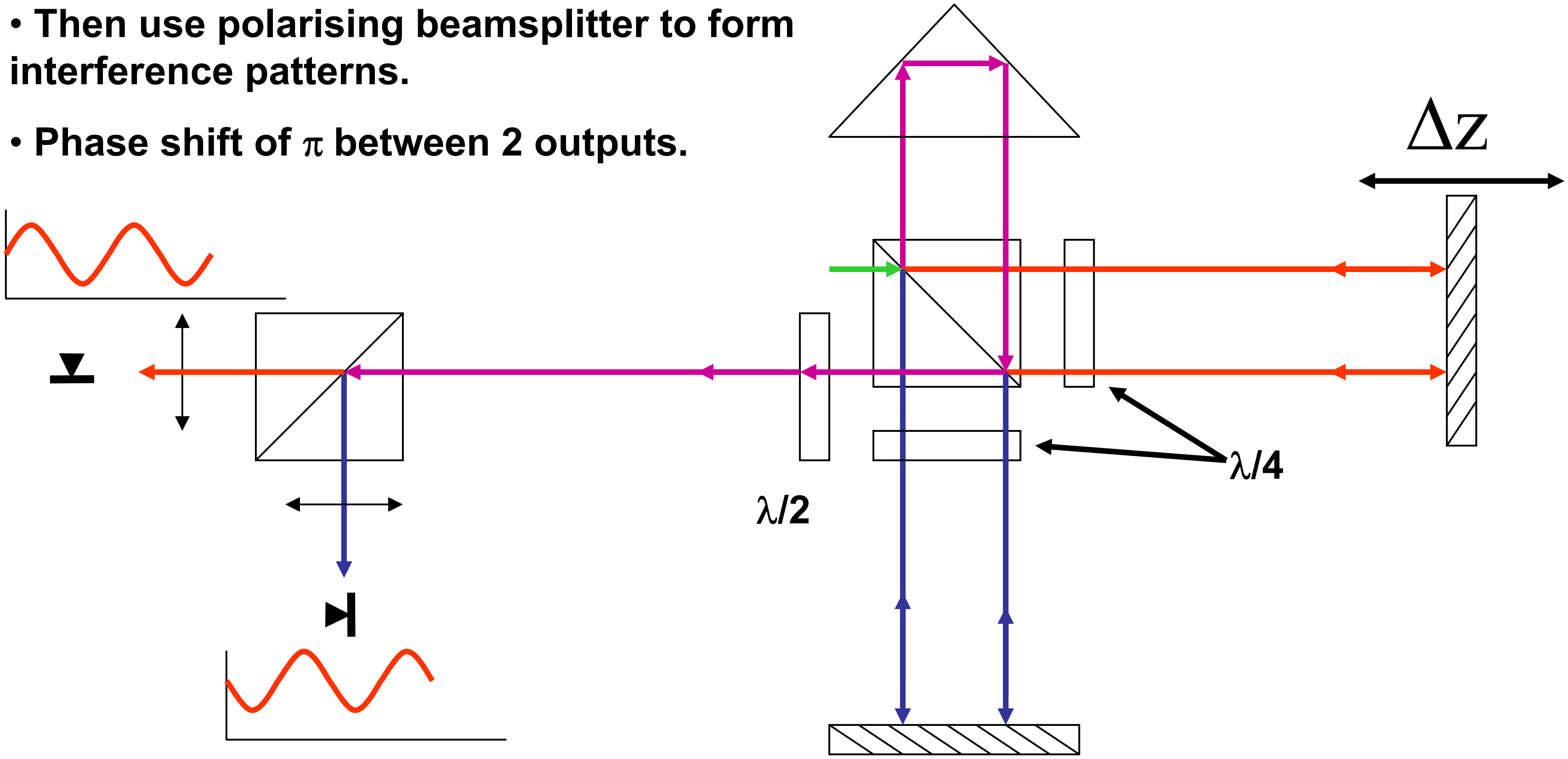
- **Make outputs interfere by resolving polarisations along 45^{O} direction.**
- **Or use half-wave plate at 22.5^{O}.**





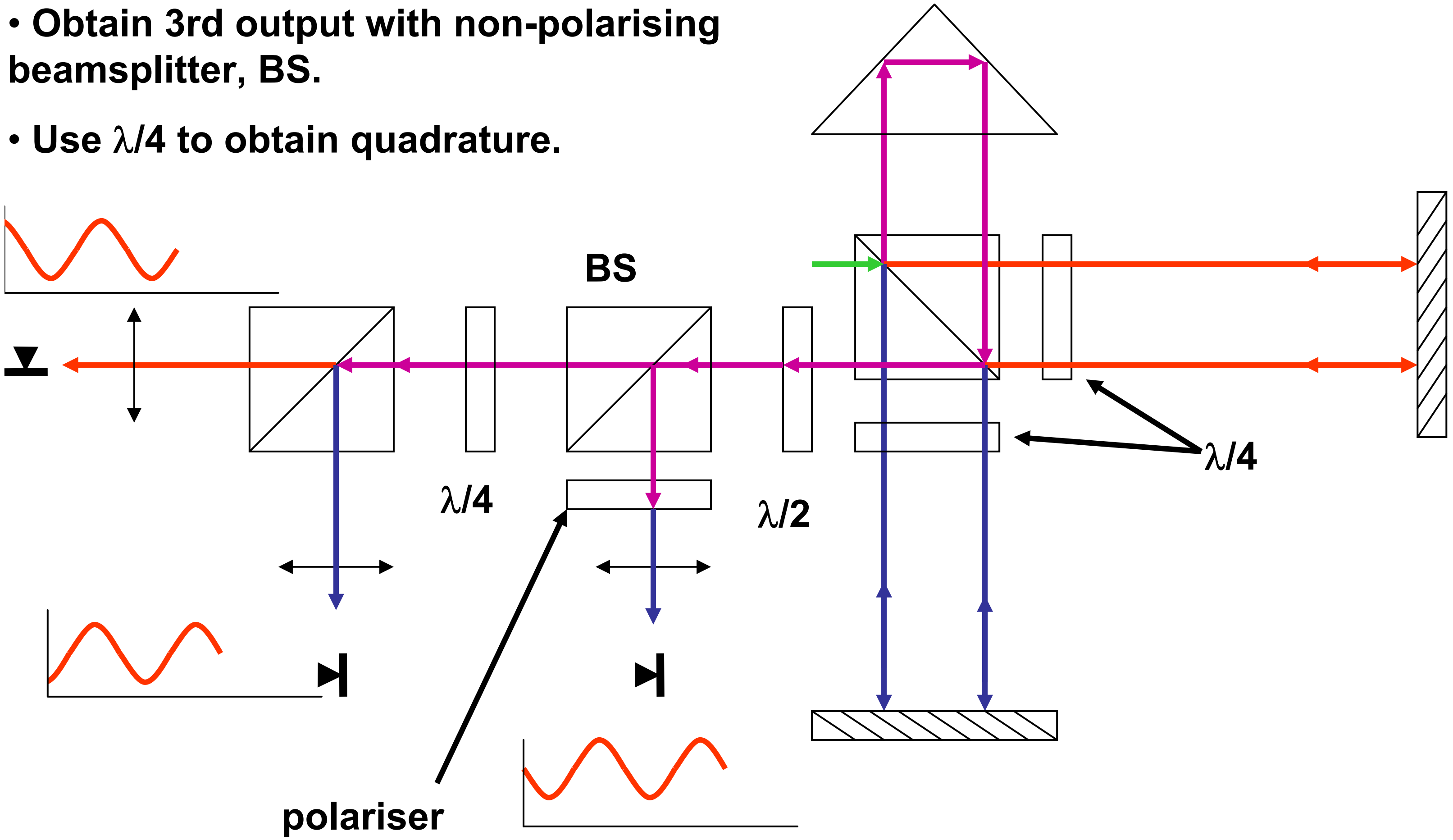
A new homodyne interferometer

- Then use polarising beamsplitter to form interference patterns.
- Phase shift of π between 2 outputs.



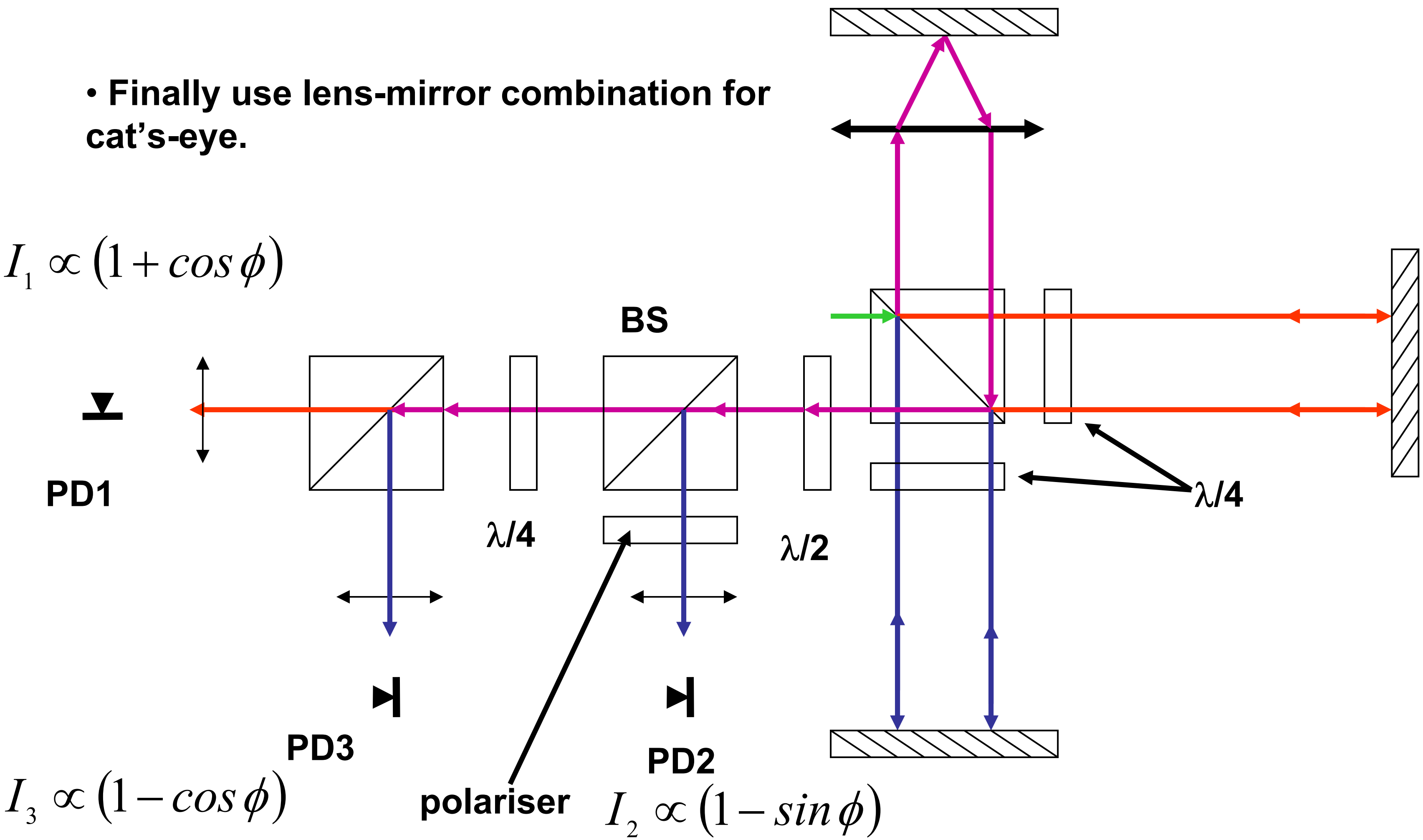
A new homodyne interferometer

- Obtain 3rd output with non-polarising beamsplitter, BS.
- Use λ/4 to obtain quadrature.



A new homodyne interferometer

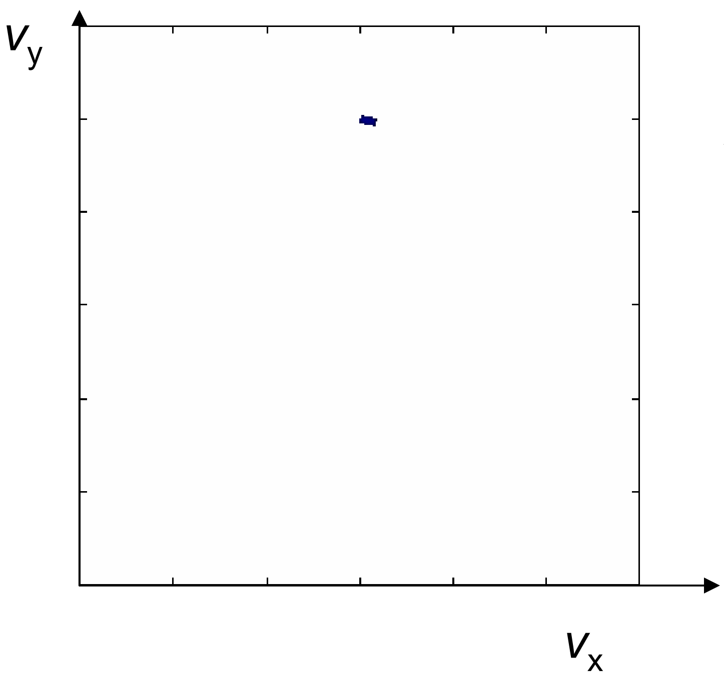
- **Finally use lens-mirror combination for cat's-eye.**



Fringe interpolation method:

- **Fringe intensities I_2 , I_3 are 90° out of phase.**

- **Motion of target mirror generates a circular Lissajous figure with I_2 , I_3 plotted as v_x , v_y .**



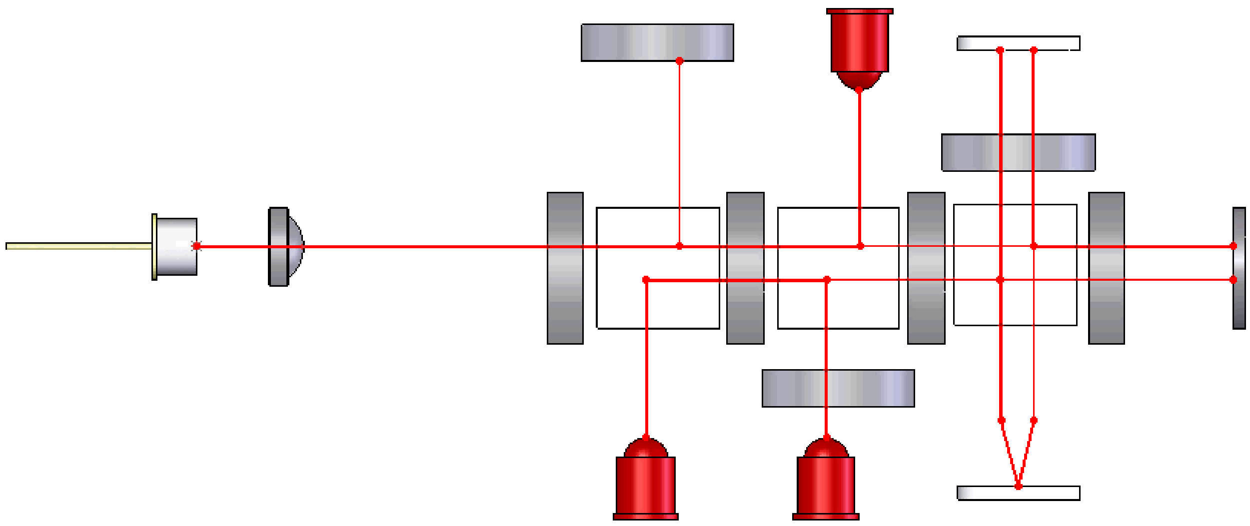
$$\Delta\phi = arctan\left(\frac{\left(v_{y2} - v_{yo}\right)}{\left(v_{x2} - v_{y0}\right)}\right) - arctan\left(\frac{\left(v_{y1} - v_{yo}\right)}{\left(v_{x1} - v_{y0}\right)}\right)$$

$$\Delta z = \frac{\Delta\phi}{2\pi} \cdot \frac{\lambda}{4}$$

$$\delta z \approx \frac{\delta I}{I}\frac{\lambda}{8\pi} = \frac{1}{\sqrt{N}}\frac{\lambda}{8\pi} mHz^{1/2}$$

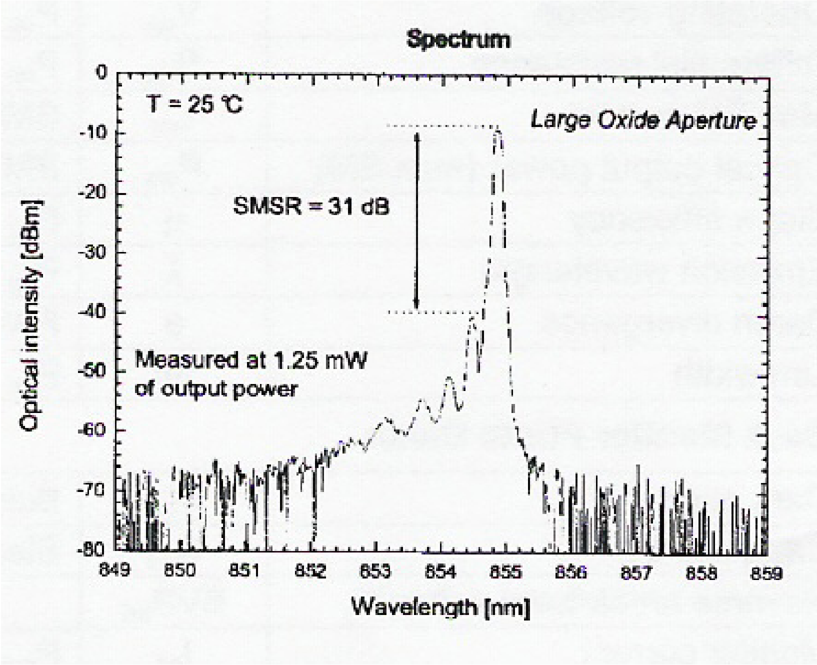
N is number of photons per second on detector.

3D CAD Optical Layout



The VCSEL laser diode

- Use VCSEL laser diode (Avalon Photonics AVAP-850SM) with pure mono-mode output over working range. No mode hops and no mode partition noise
- Operates at 850nm, 0.3-1mW



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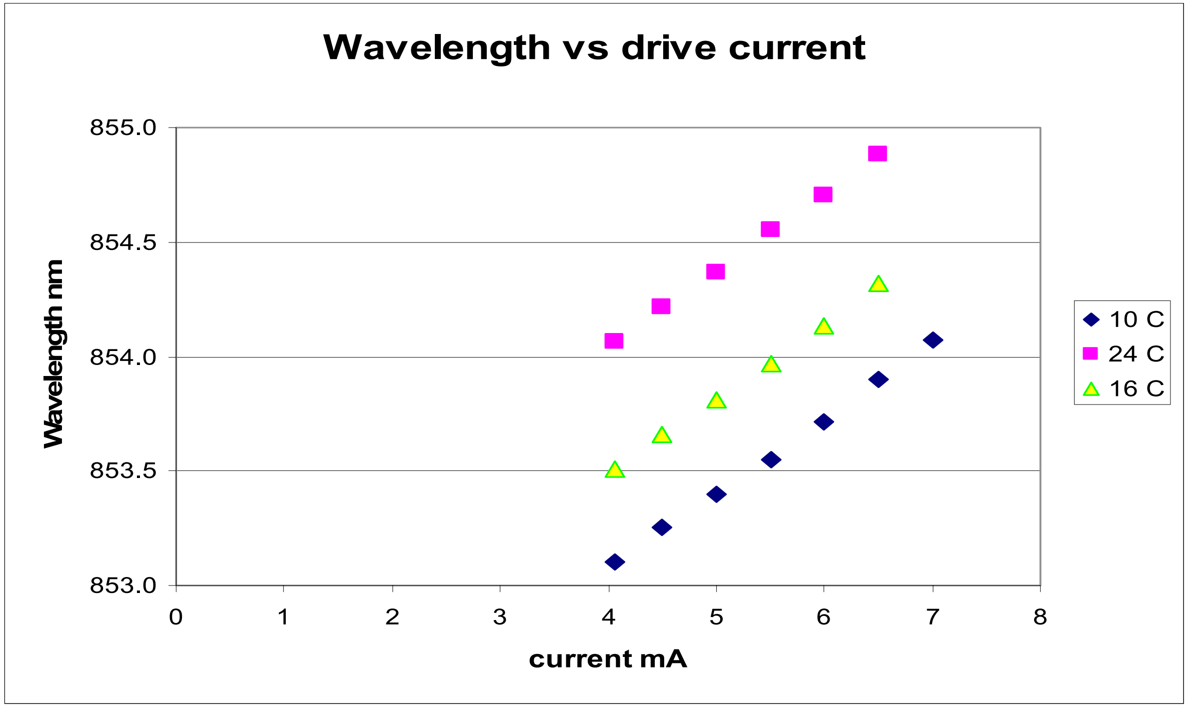
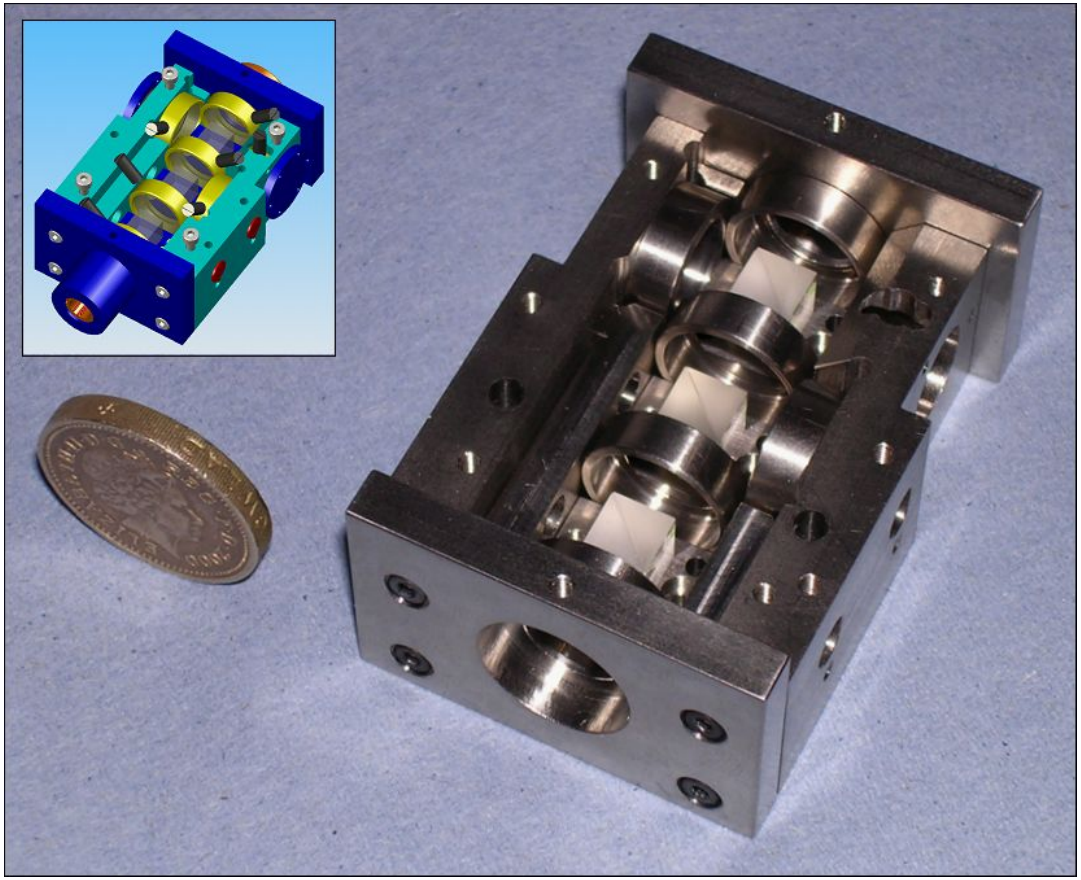
The VCSEL laser diode

- Current tuning 0.3nm/mA with range of 1nm.
- Temperature sensitivity 0.06nm/K.



The current experimental set-up

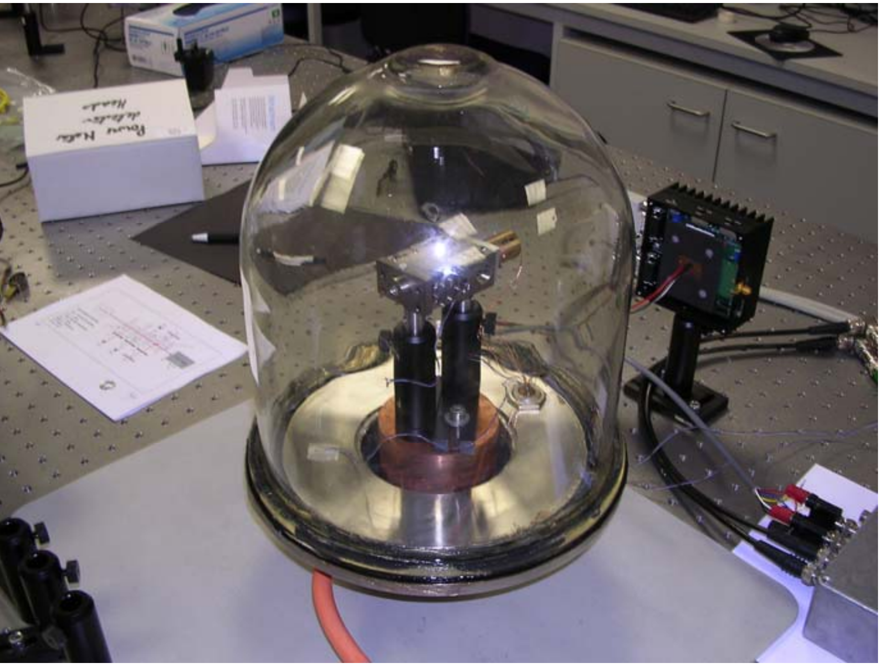
Prototype (40x70x25mm).

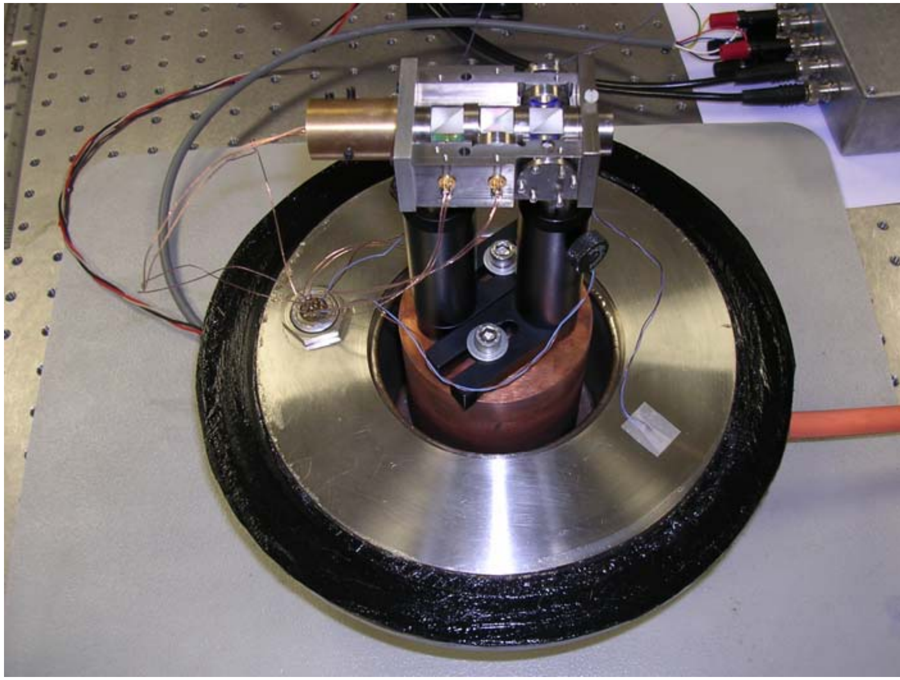


- Titanium base.
- UV bonded optics.

The current experimental set-up

- Interferometer installed within a bell jar vacuum vessel on-top of a passively damped optical bench:-
- Rotary vacuum pump achieves 10^{-3} torr (0.1 Pa).





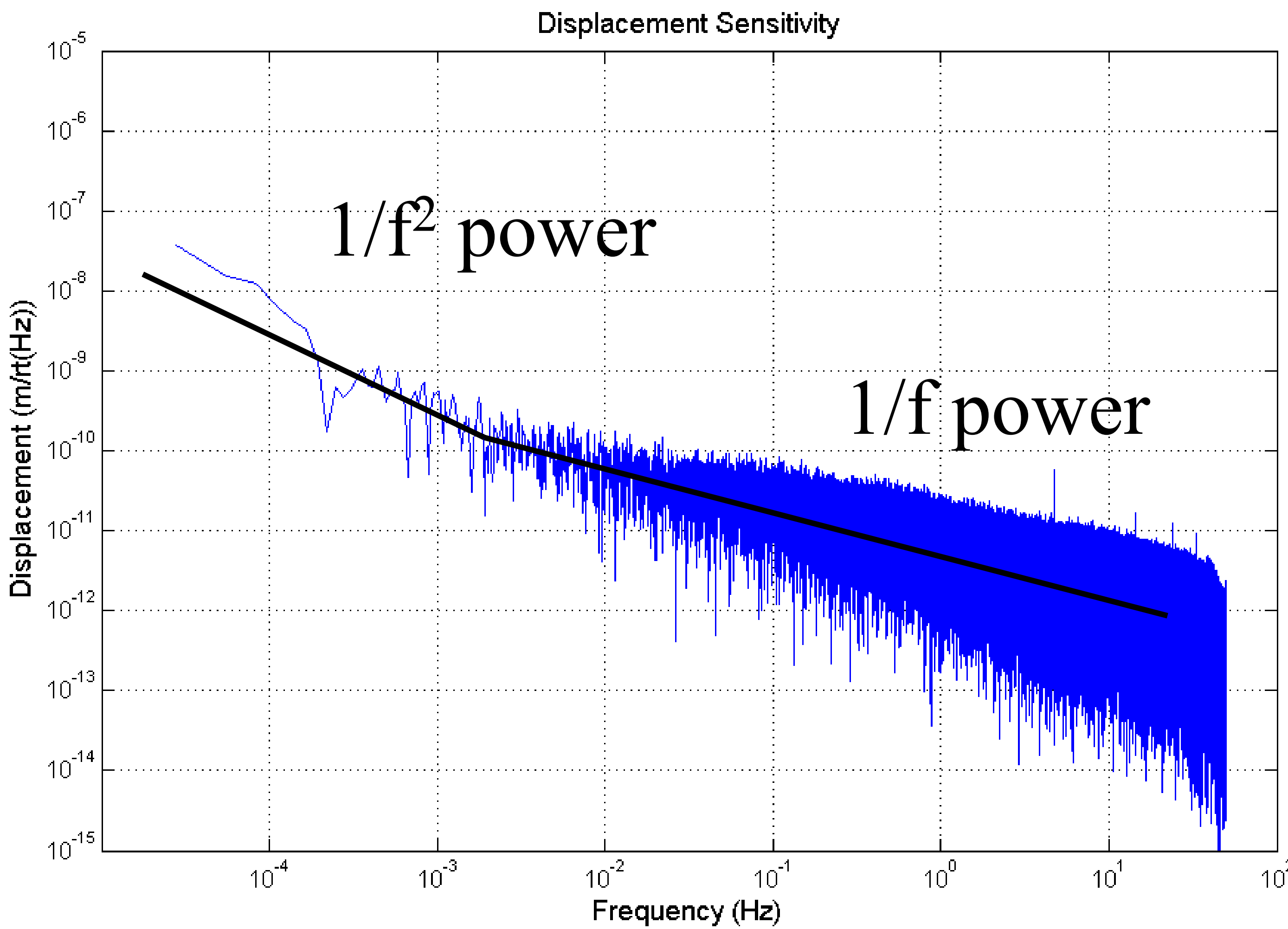
The current experimental set-up

- **Two methods for determining target mirror armlength compared with reference armlength.**

- **Incremental phase measurement:** Simply add consecutive incremental changes $\Delta\phi$. Not robust against power shut-down or target mirror motion fast enough such that we don't sample the Lissajous figure more than twice per revolution. Sensitivity is in excess of what is required.

- **Absolute interferometry:** Measure $\Delta\phi$ change induced by modulation of wavelength, $\delta\lambda$. Sensitivity is reduced by ratio $\lambda / \delta\lambda \sim 850$.

Incremental phase measurement



Results

- High frequency ($f > 10$ Hz) sensitivity 10^{-13} m/Hz$^{1/2}$ limit set by ADC noise (16-bit 50kHz sampling)
- Shot noise limit for 0.2μW is 10^{-14} m/Hz$^{1/2}$
- Medium frequency range (10^{-2} Hz < f <10 Hz) 1/f noise from input electronics noise.
- Low frequency noise determined by differential thermal expansion in interferometer armlengths
- Wavelength noise at present is suppressed by symmetry of arms (~10μm)
- Preliminary results from absolute interferometry are also limited by thermal expansion. No sensitivity to change in quasi-dc wavelength

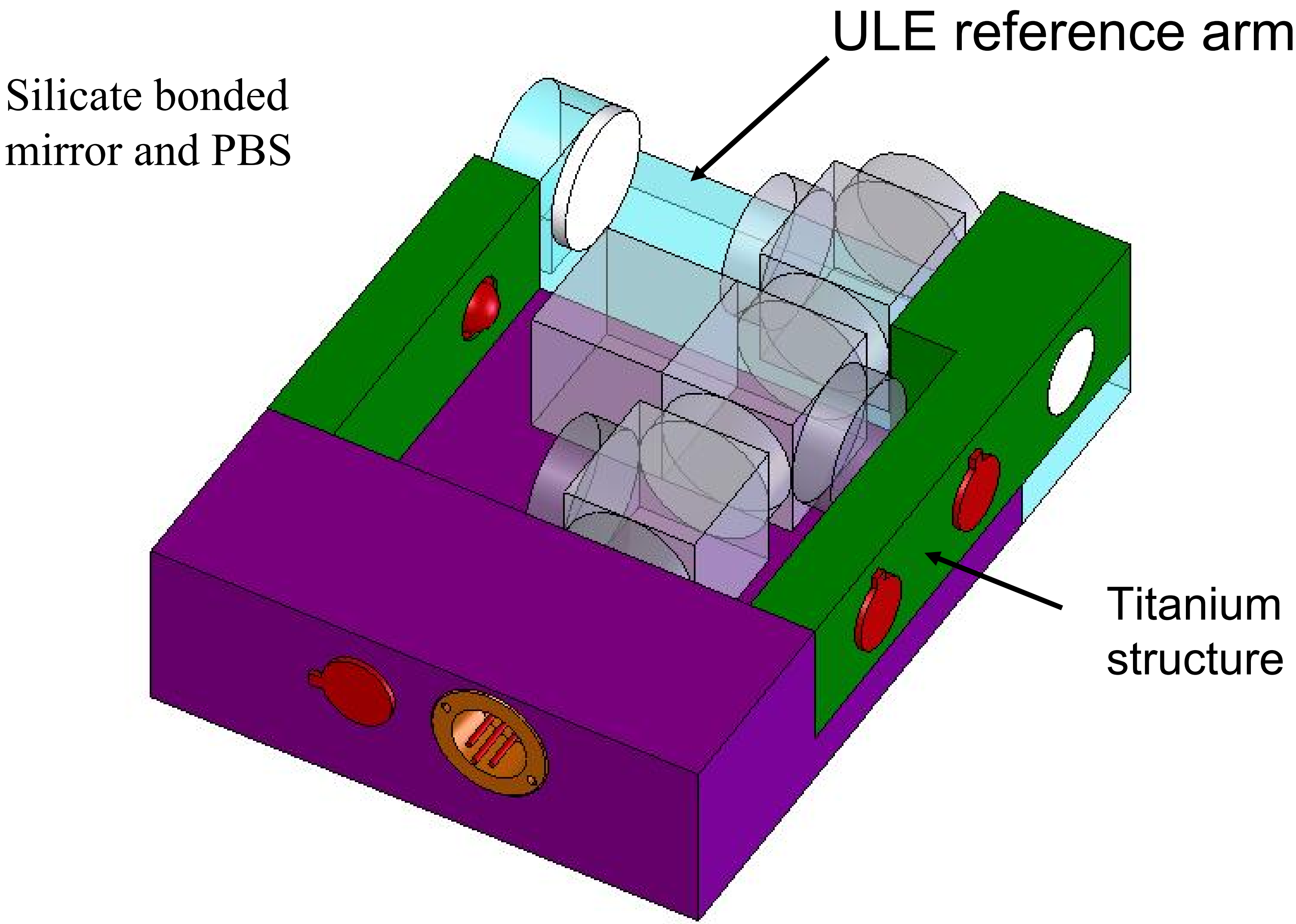
Future development

- Temperature stabilise VCSEL.

- Develop monolithic interferometer with 3 fringe outputs using silicate bonding techniques. Centring Lissajous pattern by subtracting offsets gives phase readout independent of intensity of laser.

- Pursue both absolute and incremental fringe counting methods

- Realise a robust optical readout for inertial control with goal sensitivity of 10^{-11}m$Hz^{1/2}$ over extended LISA sensitivity band.


ULE reference arm
Silicate bonded mirror and PBS
Titanium structure

Acknowledgements:

- PPARC ITF
- Members of Working Group 2